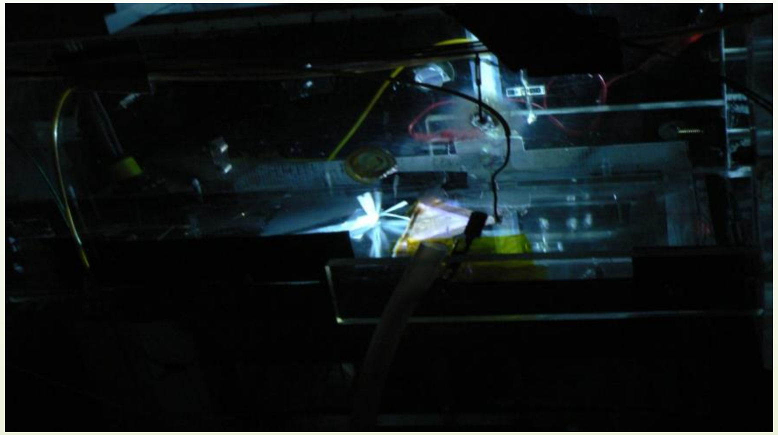
ISABE-2015-20259

Feasibility of Self Powered Actuation for Flow, Separation and Vibration Control



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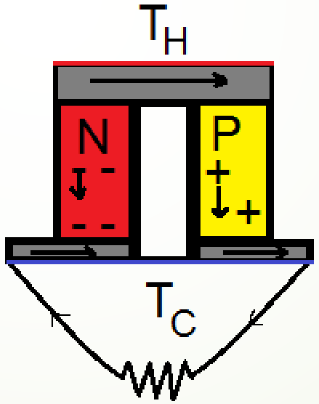
Thermoelectric Generators

- TEGs make use of the Seebeck effect - if two dissimilar metals are connected in such a way that they form a circuit, and if the junctions of those two metals are held at different temperatures, an electric potential is generated between the hot and cold junctions.

$$P = \eta Q_{TEG} = \eta \frac{T_{HJ} - T_{CJ}}{R_{TEG}}$$



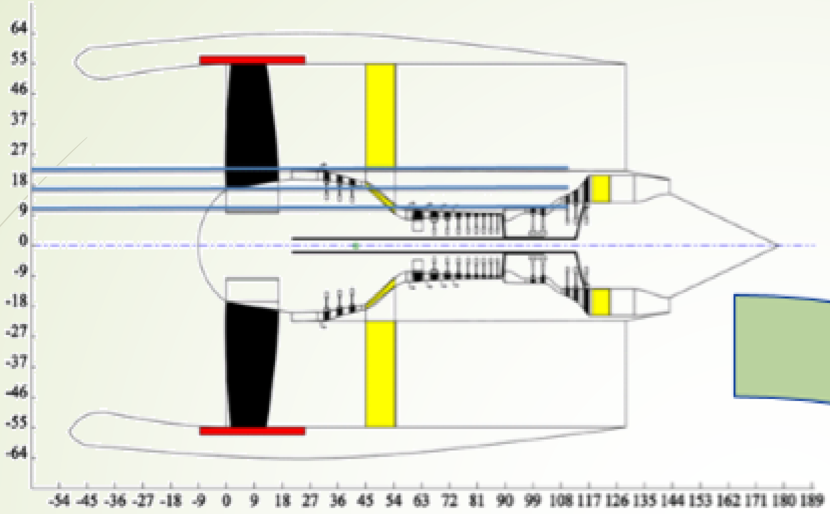
$$\eta = \frac{\Delta T}{T_h} \frac{\sqrt{1 + Z\bar{T}} - 1}{\sqrt{1 + Z\bar{T}} + T_c/T_h}$$

$$Z\bar{T} = \frac{eS^2\bar{T}}{k}$$

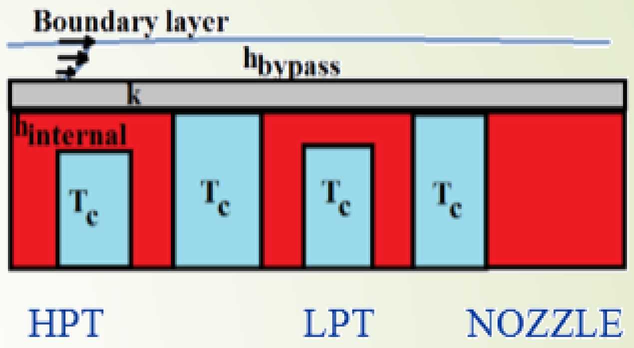
$$\bar{T} = \frac{T_H + T_C}{2}$$

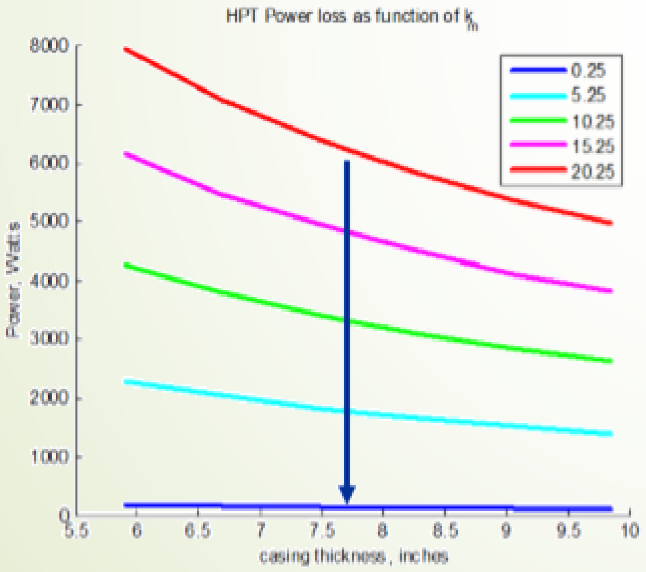
Harvesting in a Jet Engine

- In a gas turbine engine heat is lost radially through conduction in the casing walls and through the exhaust nozzle.
- Energy harvested from this temperature difference can be stored in a capacitor or battery as part of a hybrid electric engine system. (Out of scope for this talk)
- Large temperature differences (~800K) also exist between the blade outer surfaces (air that's been through combustion) and their internal surfaces (exposed to cooling air.)
- This heat transfer is not considered waste heat because the cooling air is returned to the main flow path and turns downstream blade rows.
- The benefit then of harvesting energy from the temperature difference across the thickness of a turbine blade is a local power source for active flow control, actuation or sensors.



Idealized model of Turbine and Nozzle

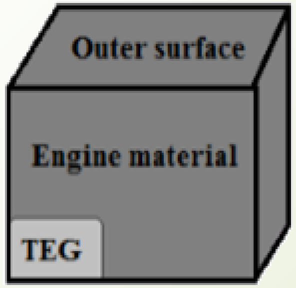




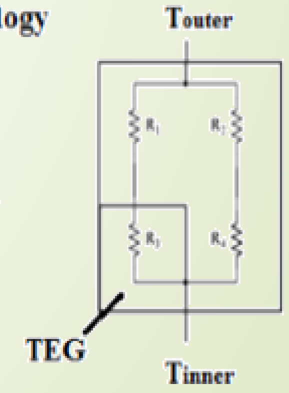
100W

$\Delta T_{metal} = +10K$

Section of engine skin with embedded TEG



Thermal-electrical resistance analogy



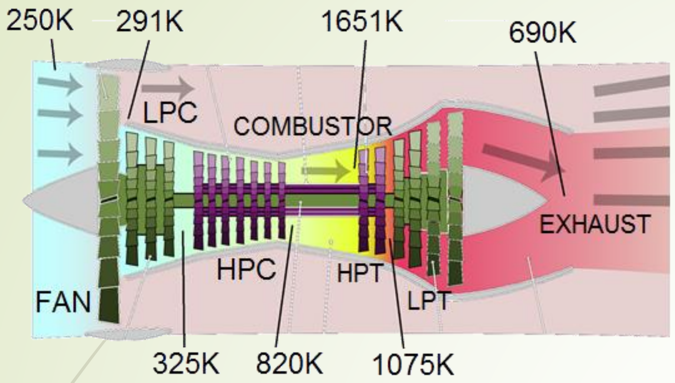


Figure 1 Cross section of a turbofan engine with representative temperatures obtained from NPSS [1] at cruise (Mach 0.85, 35k ft) for a high bypass ratio engine.

Figure 2. Turbine vanes with cooling holes

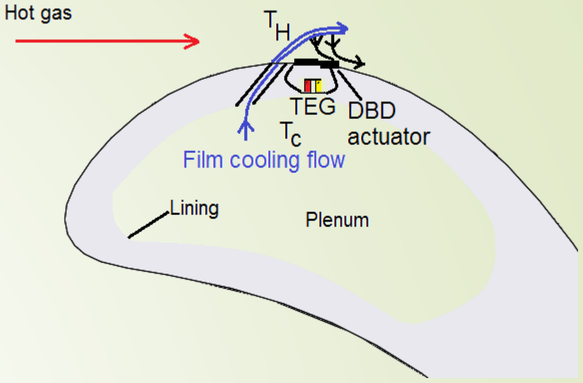


Figure 3 Self-powered DBD actuator system showing control of film cooling jet using a DBD actuator powered by energy harvested from an embedded TEG.

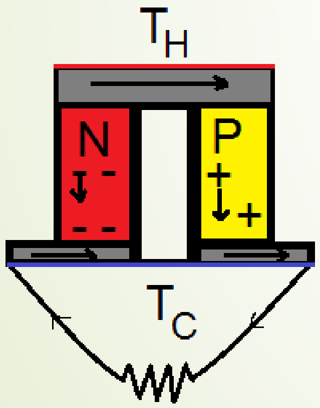


Figure 4. Schematic of a TEG (adapted from [2]).

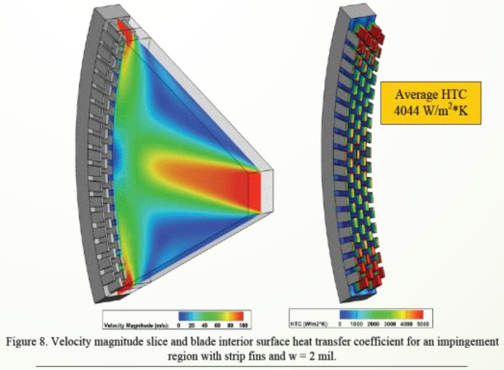


Figure 5. Micro grooves and fins in the plenum [6].

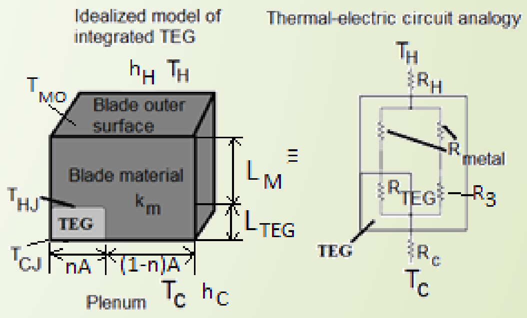
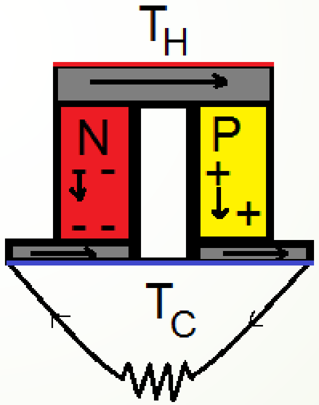


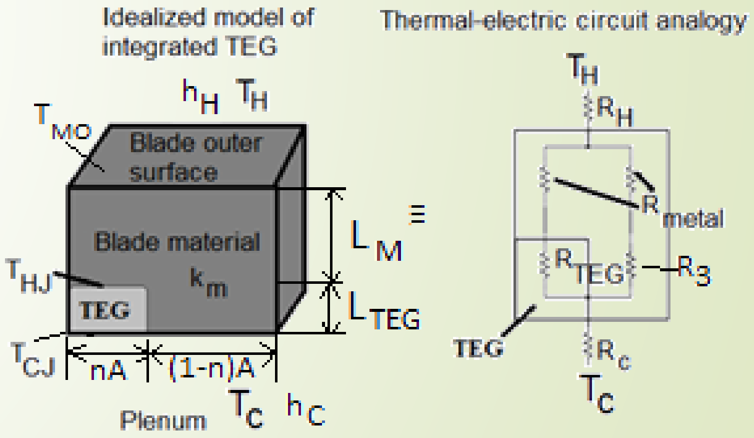
Figure 6. Left - section of blade with TEG embedded. Right - thermal circuit for TEG embedded in blade.

Power Output Simplified

$$\mathrm{P} = \frac{\eta(T_H - T_C)}{R_{TEG}}\left\{1 - \frac{1}{1 + \frac{h_C h_H L_{TEG}}{\left(1 - n + n\frac{k_{TEG}}{k_m}\right)\left[k_m(h_C + h_H) + L_m h_C h_H\right]}}\right\}$$

$$\acute{P} \sim EG\left\{1 - \frac{1}{1 + HT}\right\}$$





$$G = \frac{\eta}{R_{TEG}}, E = T_H - T_C$$

$$F = \underbrace{\frac{h_C h_H}{\left[k_m(h_C + h_H)\right]}}_{H}\underbrace{\frac{L_{TEG}}{(1 - n)}}_{T}$$

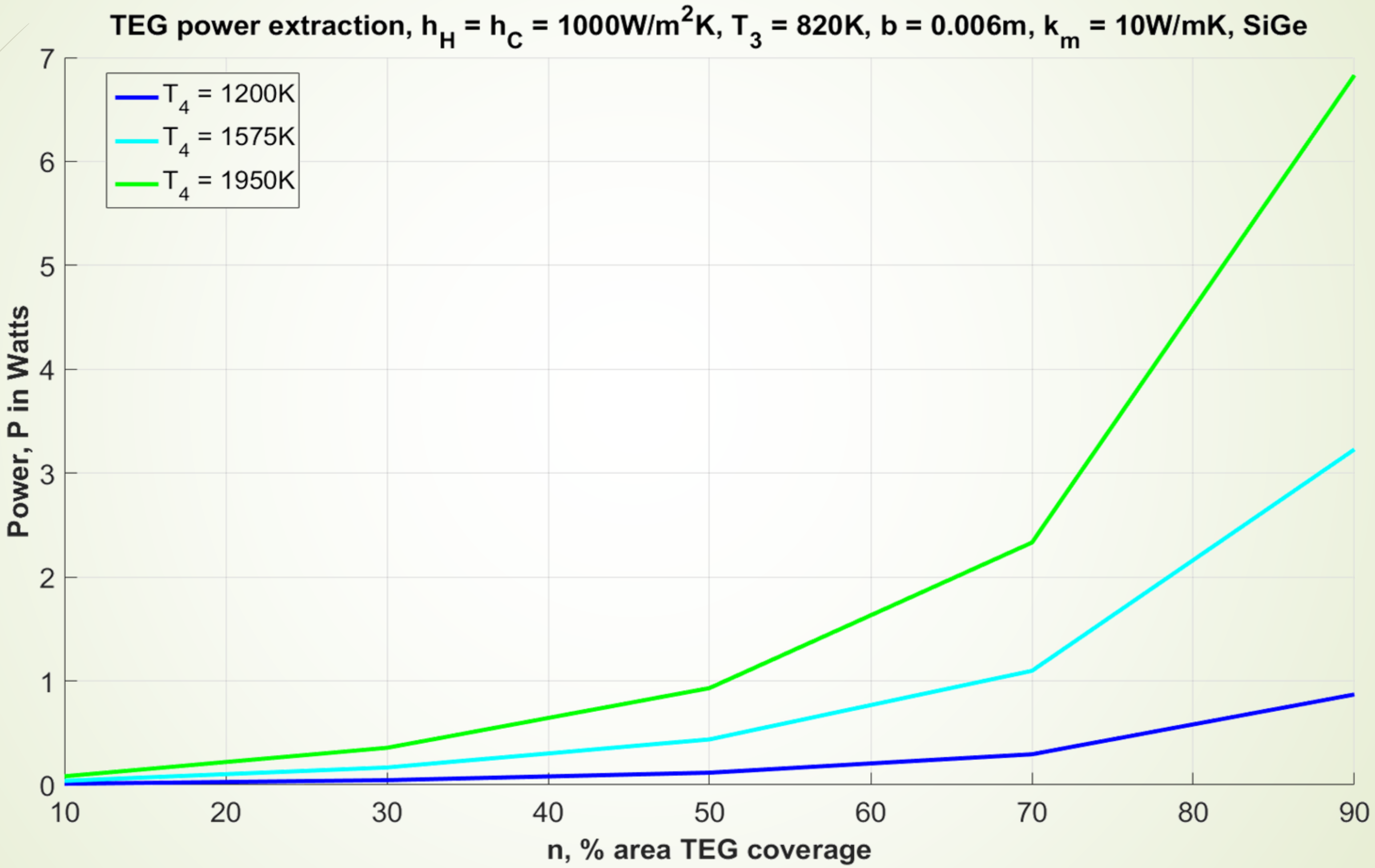


Figure 11. Power output by TEG for various hot gas temperatures, T_4 as a function of % plenum surface area used for heat extraction.

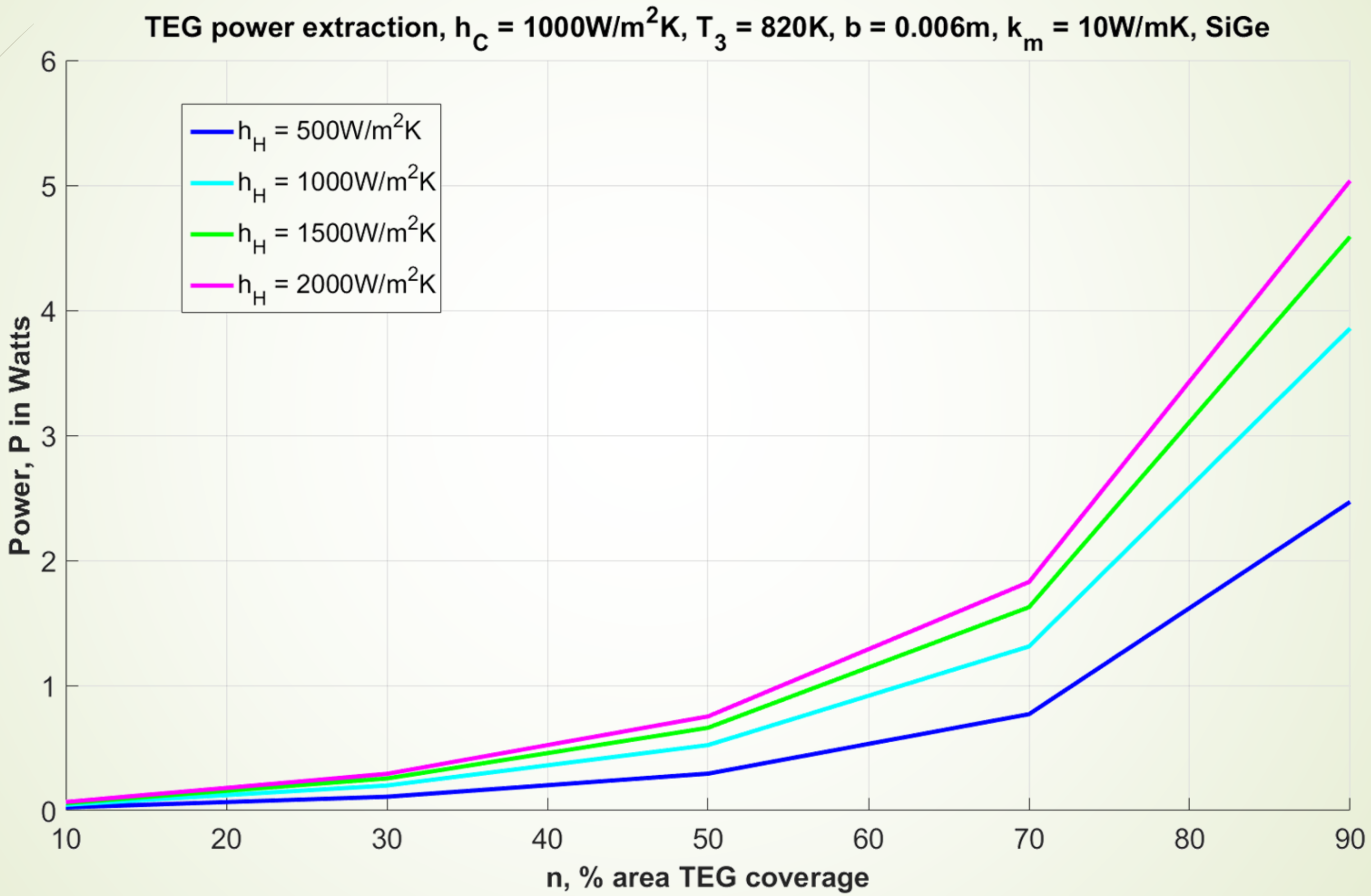


Figure 13. TEG power as a function of % plenum surface area used for heat extraction and hot gas heat transfer coefficient.

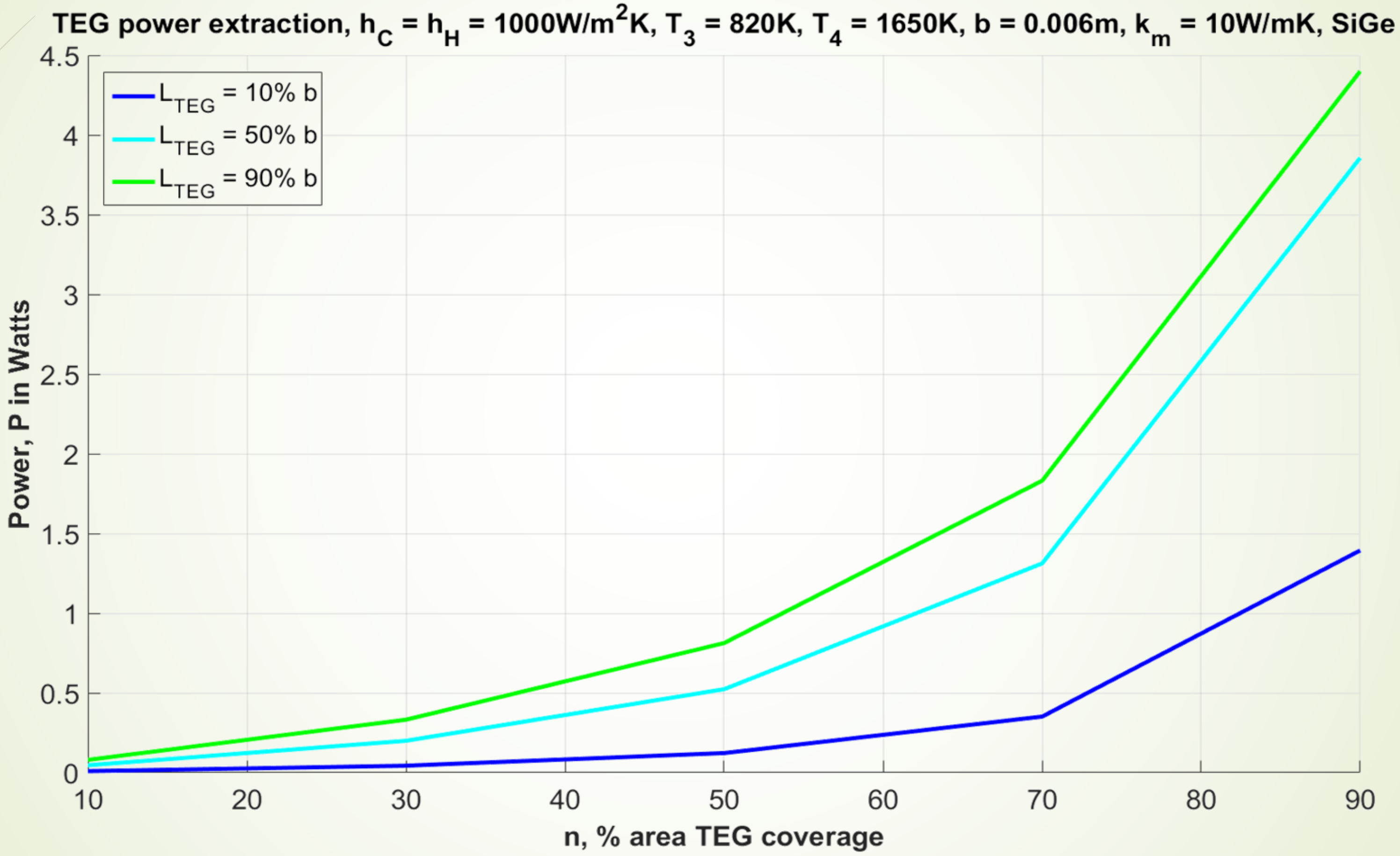


Figure 16. TEG power as a function of TEG thickness, and % plenum surface area used for heat extraction.

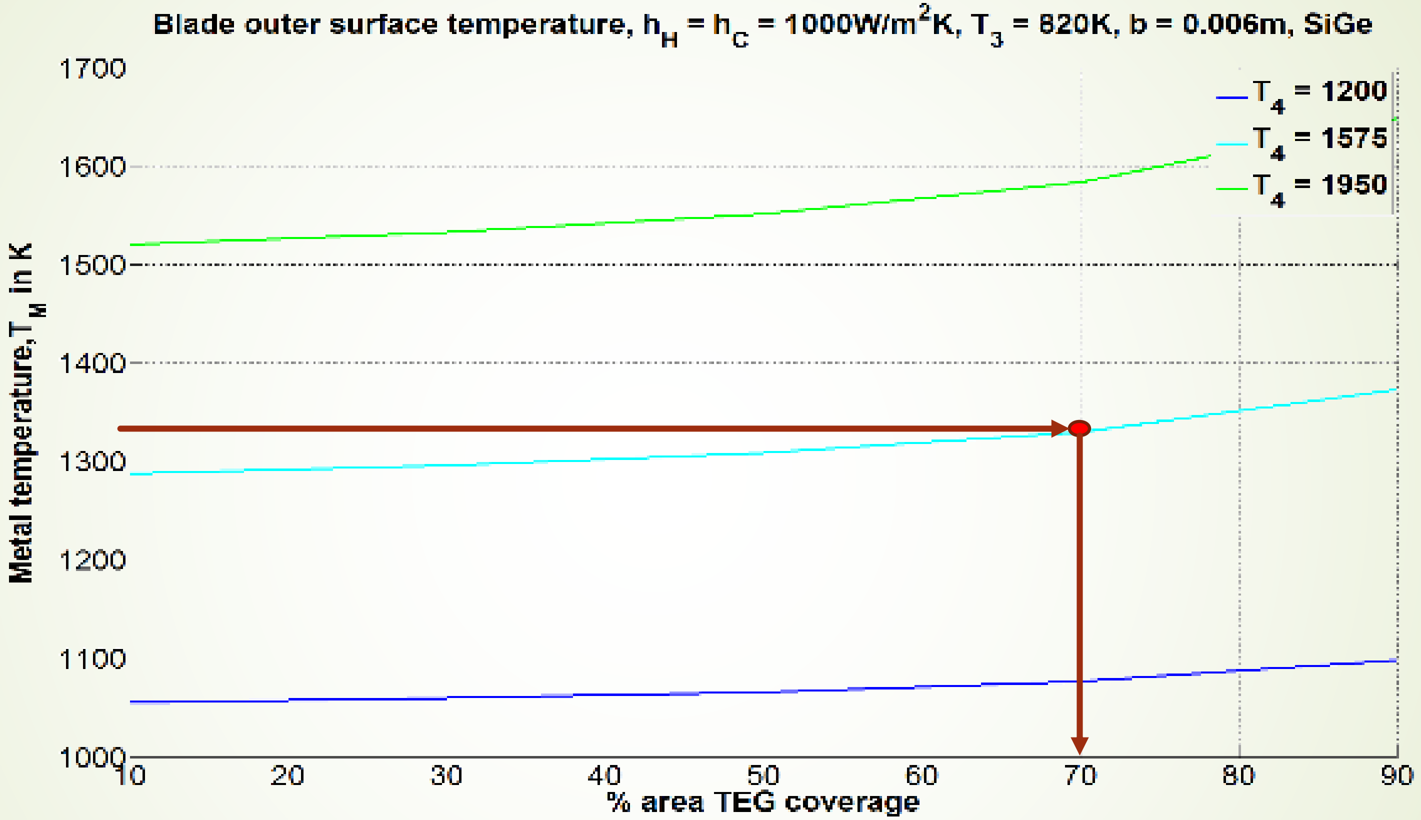


Figure 18. Blade outer surface temperature as a function of % plenum surface area used for heat extraction.

- *Blade thermal limit = 1350K (~2000°F)*
- *T4 = 1575K (2375°F).*
- *may use less than 70% of plenum surface for TEG*

Trying to collapse things…

- $\bar{P} = \frac{P}{\acute{\eta}.\Delta T_{43}}$ (Power mainly depends on ΔT_{43} for a given TEG)
- $\theta = 1 - \frac{T_4 - T}{T_4 - T_3}$
- θ = 0 corresponds to T_3
- θ = 1 corresponds to T_4

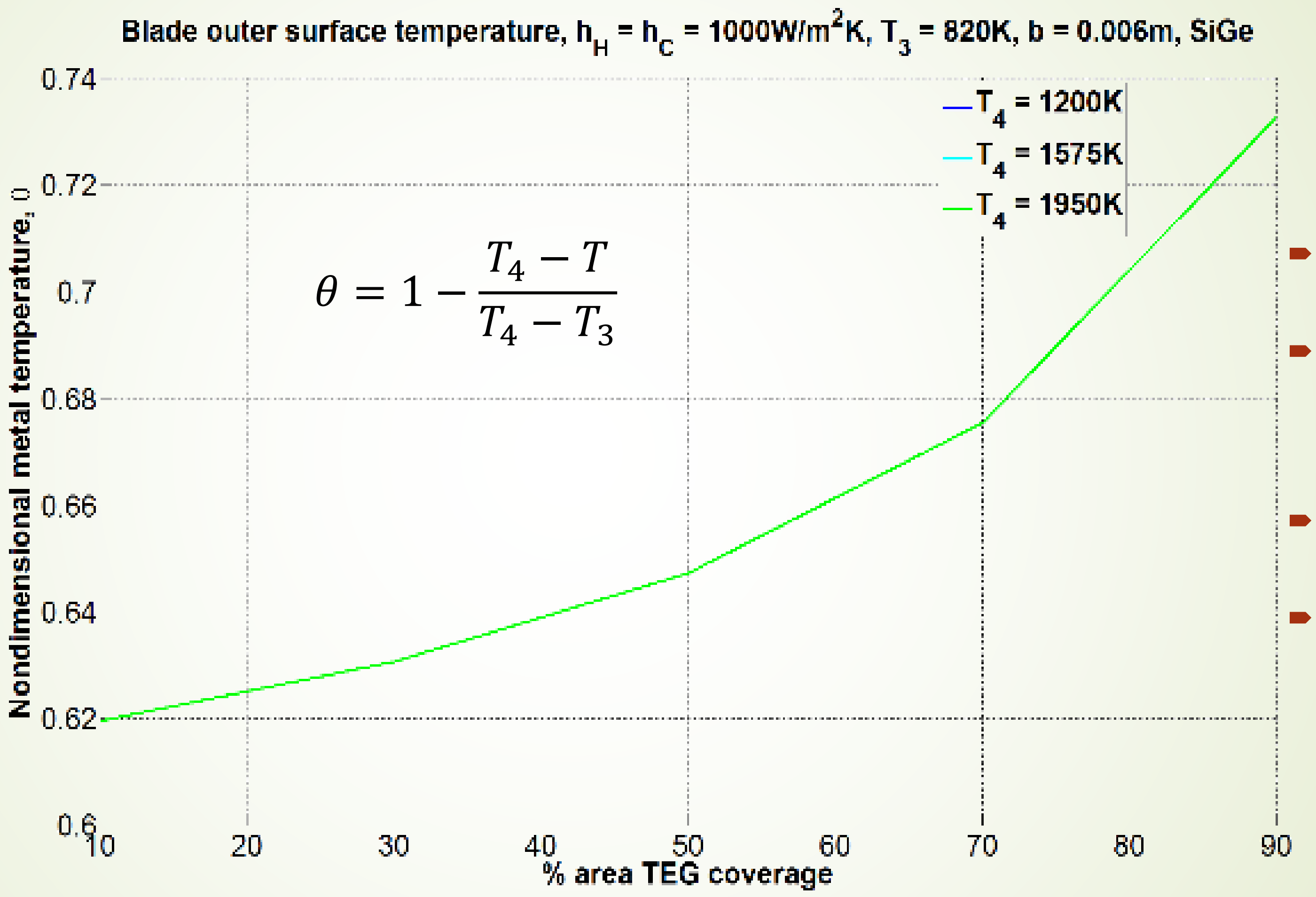


Figure 13. Blade outer surface nondimensional temperature as a function of % plenum surface area used for heat extraction.

- *Melting point of SiGe is 1600K.*
- *Assuming $T_4 = 1650K$ and $T_3 = 820K$, this corresponds to $\theta_{limit} = 0.9398$*
- *For $T_4 = 1950K$, $\theta_{limit} = 0.69$.*
- *The nondimensional hot junction temperature, θ_{HJ} must remain below this value.*

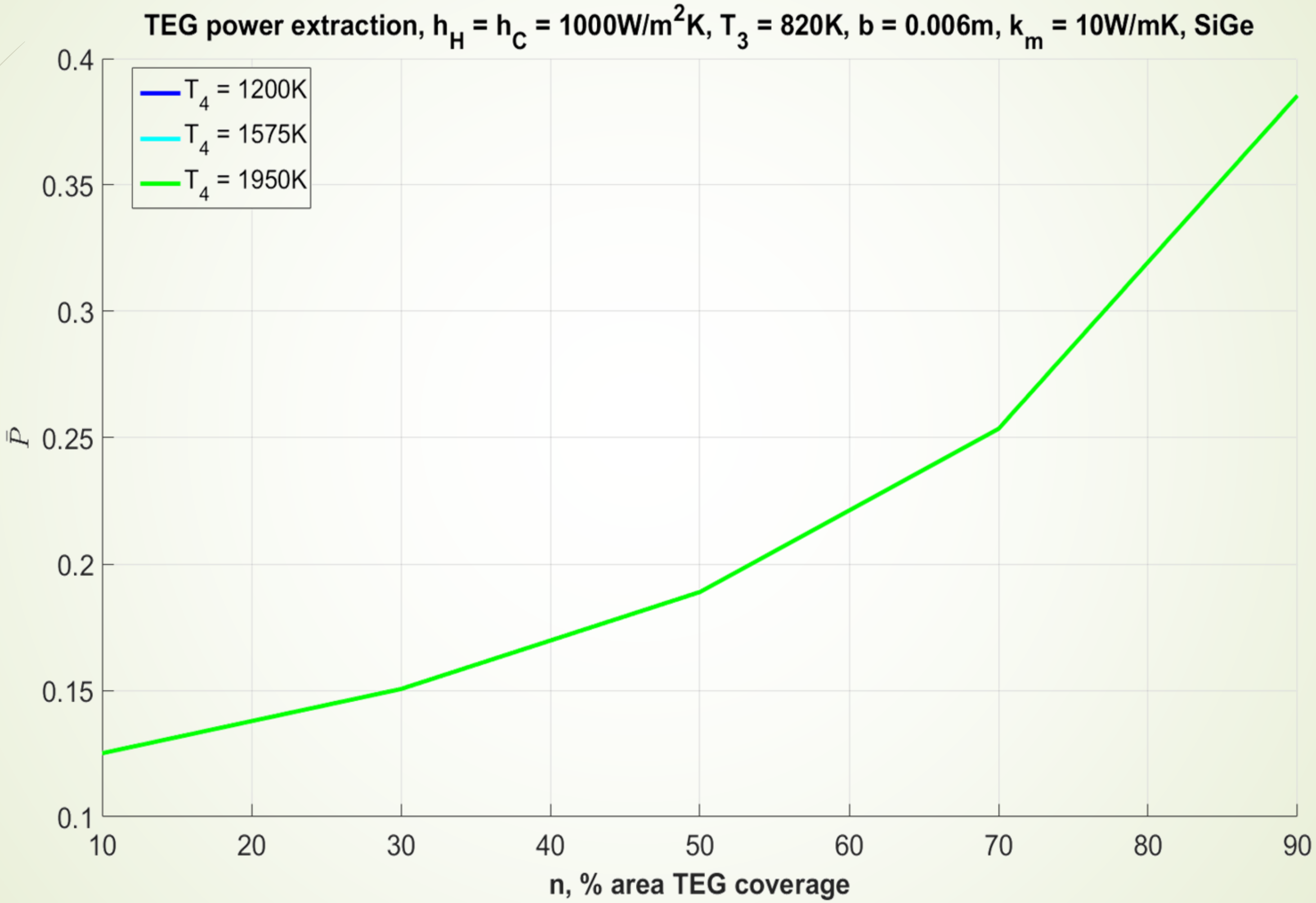
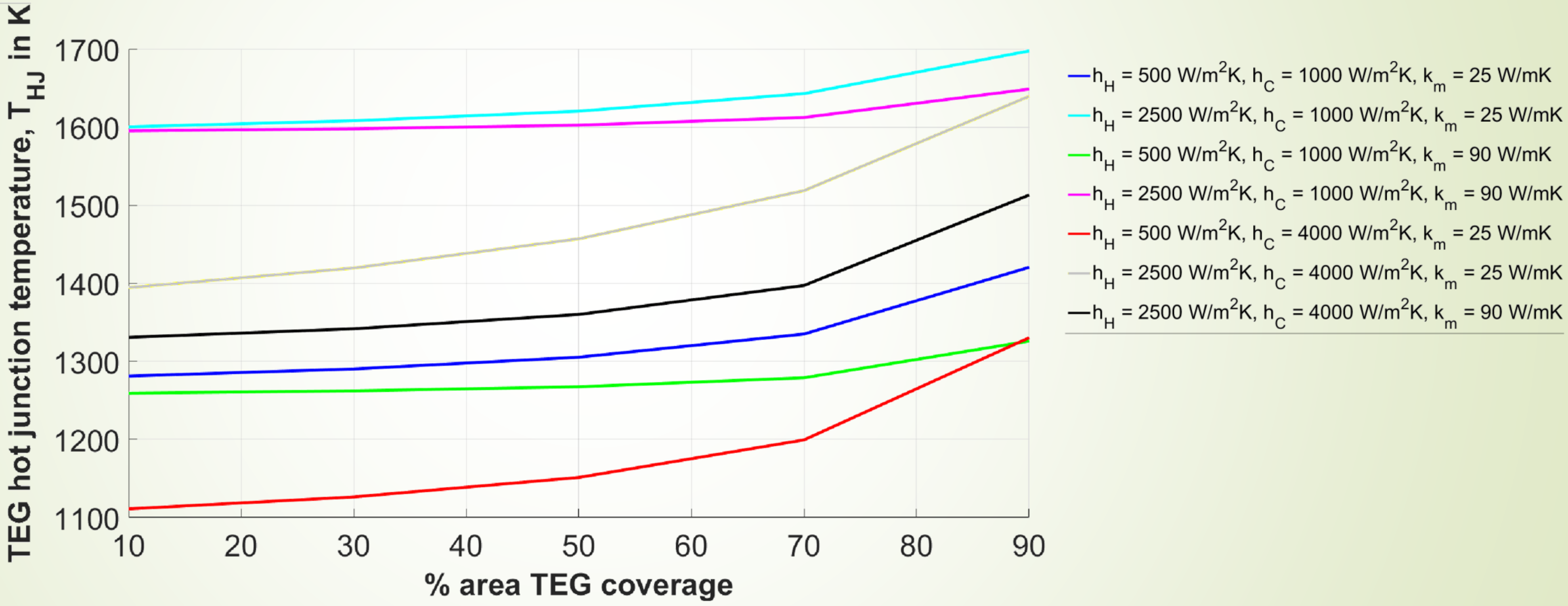


Figure 12. TEG corrected power as a function of % plenum surface area used for heat extraction.

Applying to realistic conditions…

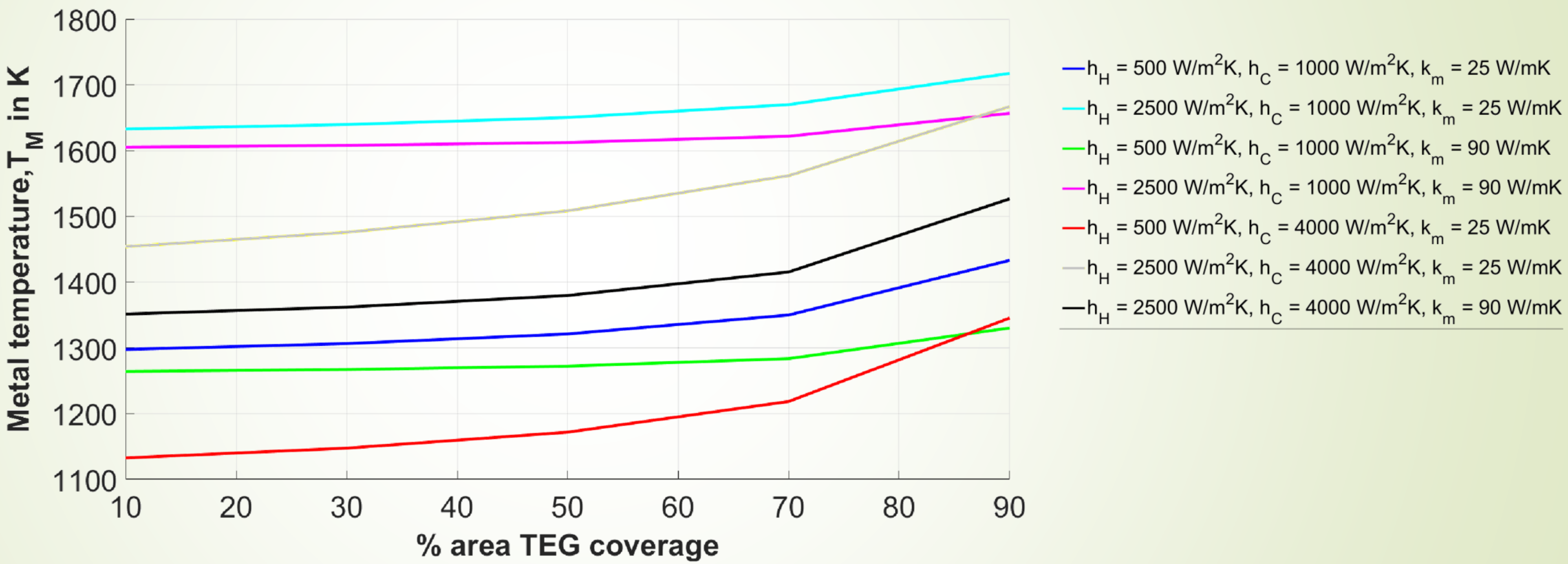
- At take-off, T_4 = 1850K and T_3 = 950K
- TEG is SiGe (high temperature limit)
- Blade thickness = 0.006m (~0.23in)
- Usable plenum surface area = .000322m^2 (0.5sq. in.)
- TEG thickness = 50% of the blade thickness
- 2 values of hot gas heat transfer coefficient, h_H considered correspond to 2 extreme cases
  - 500 W/m^2K (trailing edge regions, no film cooling)
  - 2500 W/m^2K (leading edge of vane/blade).
- Similarly for the plenum,
  - h_C = 1000 W/m^2K, h_C = 4000 W/m^2K (simple ribs and microchannels respectively)
- Thermal conductivities - 25 W/mK, 90 W/mK (single crystal superalloys and conventionally cast superalloys)

TEG hot junction temperature at T.O.



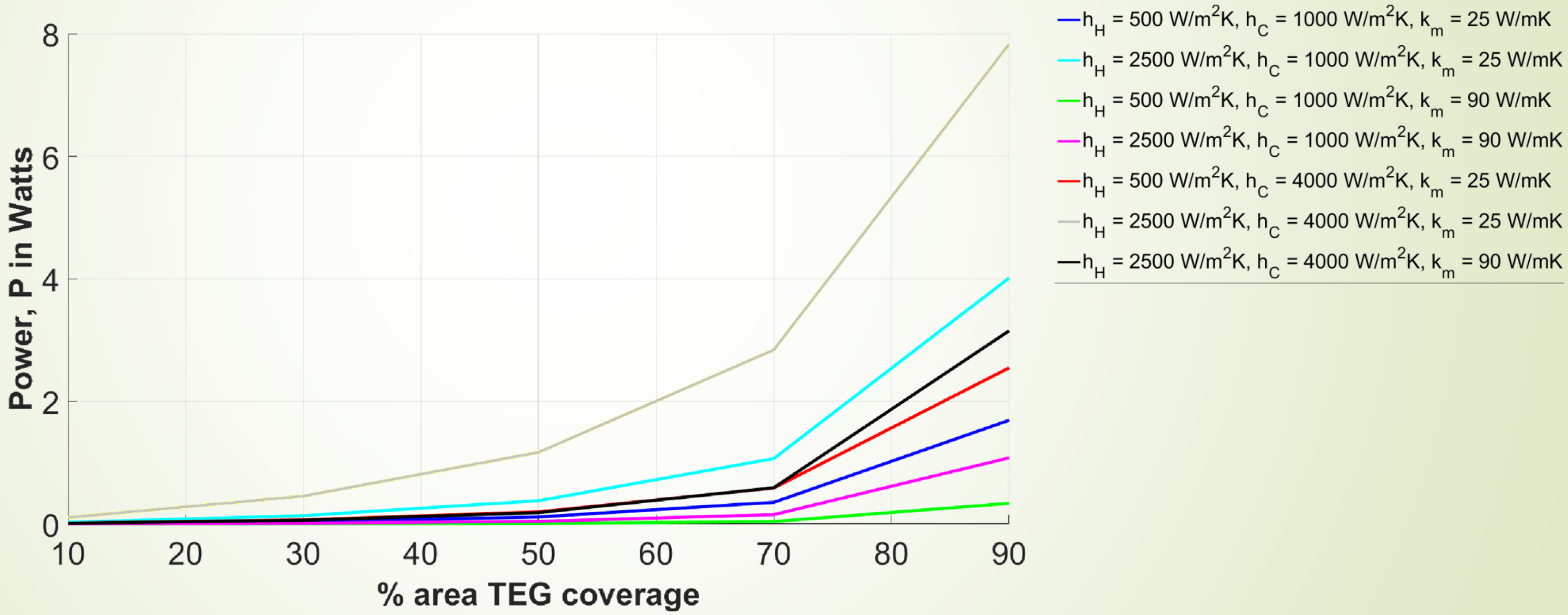
a. TEG hot junction temperature, T_3 = 950K, T_4 = 1850K, b = 0.006m, SiGe

Outer blade temperature at T.O.



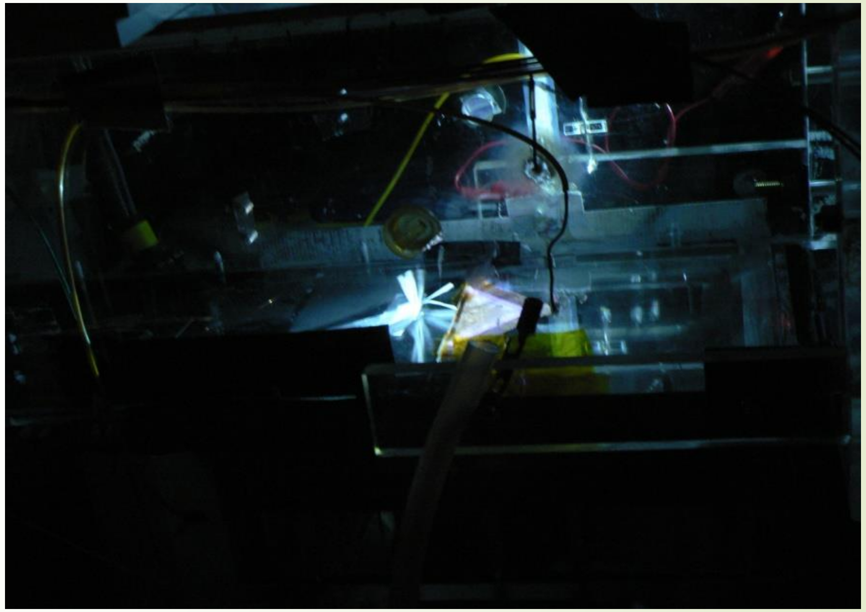
b. Blade outer surface temperature, T_3 = 950K, T_4 = 1850K, b = 0.006m, SiGe

Power output at T.O.



c. **TEG power extraction, T_3 = 950K, T_4 = 1850K, b = 0.006m, SiGe**

Blades with thermal conductivity of 90W/m.K could generate anywhere from 0.5 - 8W

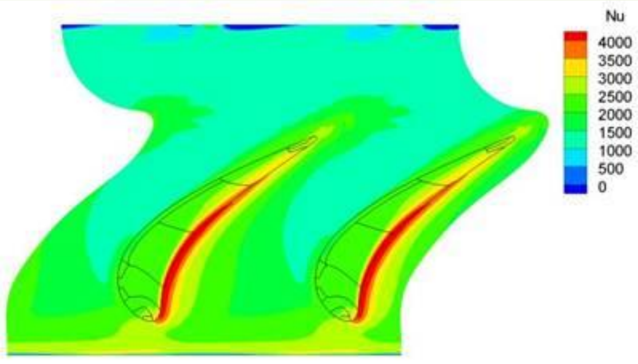


Conclusions

- *As plenum heat transfer coefficient increases, power output increases*
  - *increase in power with heat transfer coefficient is more apparent as %TEG coverage increases*
- *increasing TEG thickness from 50% to 90% only has significant benefits in the range 0.3 < n < 0.7 and is a much smaller benefit than going from 10% to 50%.*
- *increasing TEG layers leads to increased vane outer surface temperature.*

Conclusions

- There is a tradeoff that can be made between TEG power extraction and technology in the plenum to increase heat transfer coefficient.
- Film cooling effectiveness provides another control parameter (0.1 increase in effectiveness ~ 100K thermal limit increase
- Lower thermal conductivity blade provides more power but higher metal temperature
- Method to determine TEG material and parameters for integration has been shown



- Nusselt number at casing of HPT was used to get heat transfer coefficient approximations for hot gas path. The heat transfer coefficient in the hot gas path was approximated as h = k*Nu/L_seg. Average Nusselt numbers for HPT (2500), for LPT (1500) and for Nozzle (800) were used. Conductivity of air is based on local temperature.
- Bypass heat transfer coefficient is based on Nusselt number for a flat plate.
- Lamyaa A. El-Gabry, Ali A. Ameri, "COMPUTATION OF UNSTEADY HEAT TRANSFER ON THE CASING OF A TURBINE BLADE: EFFECT OF INLET TOTAL TEMPERATURE WAKE", The 9th International Congress of Fluid Dynamics & Propulsion, Alexandria, Egypt, December 18-21, 2008